Technical Memorandum:

Delta Risk Management Strategy (DRMS) Phase 1

Topical Area:

Delta Geomorphology

Final

Prepared by:
URS Corporation/Jack R. Benjamin & Associates, Inc.

Prepared for:
California Department of Water Resources (DWR)

July 31, 2007

December 5, 2008

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Subject: Delta Risk Management Strategy
Final Phase 1 Technical Memorandum – Delta Geomorphology

Dear Mr. Bagheban:

We are providing the final Delta Geomorphology Technical Memorandum (TM) (dated July 31, 2007) for Phase 1 of the Delta Risk Management Strategy (DRMS) project. Members of the Steering Committee's Technical Advisory Committee and agency staff reviewed the draft TM, and their comments were incorporated before the CALFED Independent Review Panel (IRP) review of the June 26, 2007, draft of the Risk Analysis Report. This final version of this TM addresses the IRP comments provided on the geomorphology sections of the Risk Analysis Report.

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Sincerely,

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Preamble

In response to Assembly Bill (AB) 1200 (Laird, chaptered, September 2005), the California Department of Water Resources (DWR) authorized the Delta Risk Management Strategy (DRMS) project to perform a Risk Analysis of the Sacramento–San Joaquin Delta (Delta) and Suisun Marsh (Phase 1) and to develop a set of improvement strategies to manage those risks (Phase 2).

AB 1200 amends Section 139.2 of the Water Code to read: "The department shall evaluate the potential impacts on water supplies derived from the Sacramento–San Joaquin Delta based on 50-, 100-, and 200-year projections for each of the following possible impacts on the Delta:

1. Subsidence
2. Earthquakes
3. Floods
4. Changes in precipitation, temperature, and ocean levels
5. A combination of the impacts specified in paragraphs (1) to (4) inclusive."

AB 1200 also amended Section 139.4 to read: "(a) The Department and the Department of Fish and Game shall determine the principal options for the Delta. (b) The Department shall evaluate and comparatively rate each option determined in subdivision (a) for its ability to do the following:

1. Prevent the disruption of water supplies derived from the Sacramento–San Joaquin Delta.
2. Improve the quality of drinking water supplies derived from the Delta.
3. Reduce the amount of salts contained in Delta water and delivered to, and often retained in, our agricultural areas.
4. Maintain Delta water quality for Delta users.
5. Assist in preserving Delta lands.
6. Protect water rights of the "area of origin" and protect the environments of the Sacramento–San Joaquin river systems.
7. Protect highways, utility facilities, and other infrastructure located within the Delta.
8. Preserve, protect, and improve Delta levees.…"

To meet the requirements of AB 1200, the DRMS project has been divided into two parts. Phase 1 involves the development and implementation of a Risk Analysis to evaluate the impacts of various stressing events on the Delta. Phase 2 evaluates the risk reduction potential of alternative options and develops risk management strategies for the long-term management of the Delta.

As part of the Phase 1 work, 12 technical memoranda (TMs), which address individual topical areas, and one risk report have been prepared. This TM addresses the geomorphology issues that are considered in Phase 1. The TMs and the topical areas covered in the Phase 1 Risk Analysis are as follows:

1. Geomorphology of the Delta and Suisun Marsh
2. Subsidence of the Delta and Suisun Marsh
3. Seismology of the Delta and Suisun Marsh
4. Climate Change in the Delta and Suisun Marsh
5. Flood Hazard of the Delta and Suisun Marsh
6. Wind-Wave Hazard of the Delta and Suisun Marsh
7. Levee Vulnerability of the Delta and Suisun Marsh
8. Emergency Response and Repair of the Delta and Suisun Marsh Levees
9. Hydrodynamics, Water Quality, and Management and Operation of the Delta and Suisun Marsh (Water Analysis Module)*
10. Ecosystem Impacts to the Delta and Suisun Marsh
11. Impact to Infrastructure of the Delta and Suisun Marsh
12. Economic Consequences to the Delta and Suisun Marsh

*Two separate topical areas—the Hydrodynamics topical area and the Water Management topical area—were combined into one TM because of the strong interaction between them. The resulting TM is referred to as the Water Analysis Module (WAM).

The work products described in all of the TMs are integrated in the DRMS Risk Analysis. The results of the Risk Analysis are presented in a technical report referred to as:

13. Risk Analysis Report

Taken together, the Phase 1 TMs and the Risk Analysis Report constitute the full documentation of the DRMS Risk Analysis.

The Business-as-Usual Delta and Suisun Marsh: Assumptions and Definitions

To carry out the DRMS Phase 1 analysis, it was important to establish some assumptions about the future "look" of the Delta. To address the challenge of predicting the impacts of stressing events on the Delta and Suisun Marsh under changing future conditions, DRMS adopted the approach of evaluating impacts absent major future changes in the Delta as a baseline. Thus, the Phase 1 work did not incorporate or examine proposals for Delta improvements. Rather, Phase 1 identified the characteristics and problems of the current Delta (as of 2005), with its practices and uses. This approach, which allows for consideration of pre-existing agreements, policies, funded projects, and practices, is referred to as the "business-as-usual" (BAU) scenario. Defining a BAU Delta is necessary because one of the objectives of this project is to estimate whether the current practices of managing the Delta (i.e., BAU) are sustainable for the foreseeable future. The results of the Phase 1 Risk Analysis based on the BAU assumption not only maintained continuity with the existing Delta, but also served as the baseline for evaluating the risk reduction measures considered in Phase 2.

The existing procedures and policies developed to address "standard" emergencies in the Delta, as covered in the BAU scenario, do not cover some of the major (unprecedented) events in the Delta that are evaluated in the Risk Analysis. In these instances, prioritization of actions is based on (1) existing and expected future response resources and (2) the highest value of recovery/restoration given available resources.

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This study relied solely on available data. In other words, the effects of stressing events (changing future earthquake frequencies, future rates of subsidence given continued farming practices, the change in the magnitude and frequency of storm events, and the potential effects of global warming) on the Delta and Suisun Marsh levees were estimated using readily available engineering and scientific tools or based on a broad and current consensus among practitioners. Using the current state of knowledge, the DRMS project team made estimates of the future magnitude and frequency of occurrence of the stressing events 50, 100, and 200 years from now to evaluate the change in Delta risks into the future.

Because of the limited time available to complete this work, no investigation or research was conducted to supplement the current state of knowledge.

Perspective

The analysis results presented in this TM do not represent the full estimate of risk for the Delta and Suisun Marsh. The full estimate of risk is the probable outcome of the hazards (earthquake, floods, climate change, subsidence, wind waves, and sunny day failures) combined with the conditional probability of the subject outcome (levee failures, emergency response, water management, hydrodynamic response of the Delta and Suisun Marsh, ecosystem response, and economic consequences) given the stressing events. A full characterization of risk is presented in the Risk Analysis Report. In that report, the integration of the initiating (stressing) events, the conditional probable response of the Delta levee system, and the expected probable consequences are integrated to develop a complete assessment of risk to the Delta and Suisun Marsh. In this context, the subject of this TM is one element of the Risk Analysis.

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List of Acronyms and Abbreviations

DEM	Digital Elevation Model or Map
DRMS	Delta Risk Management Strategy
DWR	California Department of Water Resources
IfSAR	Interferometric Synthetic Aperture Radar
MHHW	mean higher high water
MLLW	mean lower low water
msl	mean sea level
NAVD	North American Vertical Datum
NGVD	National Geodetic Vertical Datum
SAV	submerged aquatic vegetation
SDWSC	Stockton Deep Water Ship Channel
SRDWSC	Sacramento River Deep Water Ship Channel

1. Introduction

An integrated long-term management strategy for the Delta has to take into account not only how human actions have altered the Delta's landscape from its historic condition, but also how the landscape of the Delta could evolve in the future as a result of those actions. The shape or 'geomorphology' of the Delta dictates major physical processes driving the estuarine system, such as tidal prism, tidal range, salinity intrusion, and residence times. These physical characteristics and processes, in turn, affect ecosystem processes, flood hazards, water diversions, and the extent of wetland habitats.

There are uncertainties in developing a projection of how the Delta morphology could evolve in the future. However, based on our knowledge of the physical processes that have shaped and will continue to shape the evolution of the Delta landscape, it is possible to approximate the range of possible future 100-year morphologic outcomes at the estuarine scale.

This report summarizes our current knowledge of the historic conditions, anthropogenic changes, present status, and potential future trajectories of the geomorphology of the Delta based on existing published and readily available information. The primary tool used in characterizing and projecting Delta morphology is a set of hypsometric curves that describe the elevation-area relationships within the Delta as a whole, for past, present, and potential future conditions. In evaluating future conditions, we have selected three extreme hypothetical 'book end' scenarios: (1) the 'business as usual' scenario where the levees remain intact and are maintained over the next 100 years (as defined by the DRMS Management Team), (2) complete levee failure at year zero with subsequent evolution of flooded islands, and (3) complete levee failure at year 100. Our analysis of the change in morphology is based on our understanding of how different geomorphic elements (channels, wetlands etc.) within the tidal Delta will respond to current or anticipated trends in the physical processes that shape this landscape.

2. Geomorphic Evolution of the Historic Delta

2.1 Holocene Evolution, Form, and Process

The geomorphology of the Sacramento-San Joaquin Delta before the period of Euro-American colonization was dominated by intertidal landscapes in dynamic equilibrium with sea-level rise and sedimentation. This landscape of tidal marsh, tidal channels, deltaic distributary channels, and natural levees was resilient to long-term progressive environmental change and short-term perturbations. The development of equilibrium conditions reflected the long time frame over which the wetland landscapes became established and the relatively constant rate of relative sea-level rise over the last 5,000 years.

In the Delta, relative sea level rise is the sum of eustatic (global) sea-level rise, tectonic land movements and local subsidence (typically soil decomposition and consolidation). During the last glacial period, around 15,000 years ago, relative sea level was approximately 300 ft lower than today and the Pacific coast was at least 6 miles west of its present position. During this time the Delta formed part of the arid alluvial floodplain of the Central Valley and alluvial sand deposits together with aeolian sand deposits underlie most of the late Holocene Delta soils. At Browns Island at the seaward end of the Delta, these deposits have been dated between 6,700 and 6,200 years ago indicating no brackish-marine influence in the Delta at this time (Goman and Wells, 2000).

Between 10,000 and 5,000 years ago relative sea-level rise was rapid, approximately 6 mm/yr, then about 5,000 years ago the rate slowed to about 1-2mm/yr (Goman and Wells, 2000; Byrne et al., 2001; Meyer, 2003) (Figure 1). At this time sea water encroached landward through the Carquinez Strait into the lowlands that became Suisun Bay and the Delta. It is likely that early in the formation of the Delta landscape (6,000 to 5,000 years ago), the rate of relative sea-level rise created more accommodation space than could be filled by the flood-borne sediment supply, and brackish sedimentary environments transgressed landward. This period of time saw the widespread deposition of organic silt and clay across the alluvial floodplain surface. At Browns Island, the unit comprises clay with organic laminations and is interpreted as deposits formed in incipient brackish tidal marshes, which were drowned frequently (Goman and Wells, 2000). The long-term trend through the silt-clay unit (at Browns Island) is towards less frequent inundation as the sedimentation rate gradually overtook relative sea-level rise.

The historic Delta landward of Browns Island evolved laterally as two overlapping geomorphic units. The Sacramento Delta to the north comprised about 30% of the total area and extended as far as Sherman Island to the west. It's morphology was created by the interaction of rising sea level, alluvial river-flood deposition and tidal marsh peat formation. This created an inland 'bird's foot delta' of distributary channels bordered by higher supratidal natural levees, and surrounded by marsh plains (Figure 2).

In contrast, the larger south-centrally-located San Joaquin Delta (about 70% of the total area), with its relatively small flood flows and low sediment supply, formed as an extensive uniform freshwater tule (assemblage of bulrush (*Scirpus* sp.), cattails (*Typha* sp.) and common reed (*Phragmites* sp.) tidal marsh dominated by tidal flows and organic (peat) accretion (Atwater and Belknap, 1980). Here the channel system was determined almost entirely by tidal flows that created an extensive sinuous dendritic channel network (Figure 2). Due to the differential amounts of inorganic sediment supply, the peat of the south-central Delta (San Joaquin River system) grades northwards into peaty mud and mud towards the natural levees and flood basins of the Sacramento River system (Atwater and Belknap, 1980). This is reflected in the thickness of peat across the Delta which can be up to 30 ft thick in the central Delta thinning towards the north and south.

At the margins of the Delta the freshwater tidal marshes merged with flood basin marshes at slightly higher elevations. Although the wetland species were the same, the underlying soils were different because the flood basins dried out every summer, preventing peat accumulation.

In the Delta, for the last 5,000 years to the 1850s, relative sea-level rise was balanced by vertical marsh growth through biomass accumulation and sediment deposition (Atwater et al., 1979). A transition from deposition of organic silt-clay to peat formation in the Delta largely reflects the decline in inundation frequency and the maturation of the marsh plain towards mean higher high water (MHHW) elevations. The resulting freshwater tidal marshes developed because a relatively large freshwater inflow compared to the size of the tidal prism sustained a low salinity, which supported highly productive organic peat formation through tule growth (Simenstad et al., 2000; Byrne et al., 2001). The large roots of the tule created an organic fabric that supported and aided rapid vertical growth. The living surface was maintained within the intertidal zone (natural habitat), and marsh organic accretion (injection of roots and rhizomes, and incorporation of surface litter) was able to sustain vertical growth at rates in excess of relative sea-level rise. The gradual accumulation of the organic and inorganic sediment must have also offset the loss and compaction of existing peat.

The freshwater tidal wetland plants of the Delta are able to colonize by rhizome expansion down to elevations of one foot below mean lower low water (MLLW) (Simenstad et al., 2000). This means that extensive mudflats did not form and large wind fetches only occurred where large tidal channels were oriented in the direction of the prevailing wind.

2.2 Processes Sustaining the pre-Euro-American Landscape

2.2.1 Sedimentation and Peat Formation

The main historic source of inorganic sediment to the Delta was Sacramento River floods (Wright and Schoellhamer, 2004). Some of this sediment would have been captured on the Delta marsh plains but most was deposited in the shallows of Suisun and San Pablo Bays. A large portion of these deposited sediments were then resuspended by wind-wave and tidal action and recirculated into the estuarine system (Ruhl et al., 2001; Schoellhamer, 2002), where a portion would have migrated back up-estuary along the channel bed, driven by the vertical baroclinic residual circulation. This process created a turbidity maximum/entrapment zone within the water column that migrated from San Pablo Bay to the western Delta depending on the relative magnitudes of river flow and tidal forcing. Proximity to the turbidity maximum affected sediment deposition in the extreme western Delta at Browns Island.

Differential spatial sediment supply from the Central Valley rivers had a profound impact on the types and sustainability of habitats in the pre-Euro-American landscape of the Delta. Thick sequences of organic material are found almost exclusively in the south-central Delta indicating a set of conditions over the last 5,000 years that promoted the accumulation and preservation of plant remains and minimized the deposition of inorganic sediment. Here, the natural levees were poorly defined along the San Joaquin River and its tributaries, due to moderate flood peaks and a relatively low sediment supply, and hence they were unable to confine flood water to induce settlement of fine sediment (Atwater and Belknap, 1980). Deposition patterns in the northern Delta were more complex because high flood flows and relatively high sediment delivery created a system of supratidal natural levees along the distributary channels of the Sacramento River. These levees strongly influenced the tidal drainage of adjacent interior marshes.

The high productivity of the freshwater tidal marsh vegetation creates large volumes of organic detritus that accumulates in the anoxic conditions that prevail in saturated soils on the marsh plain. This means that peat accumulation rates match the rate of increase in sea level rise and water table elevation within the marsh soils.

2.2.2 Relative Sea-level Rise

It is possible that very early in the formation of the Delta landscape (prior to 5,000 years ago), the rate of relative sea-level rise outpaced sedimentation and peat formation (Goman and Wells, 2000). Continued slowing and stabilization of relative sea-level rise after 5,000 years ago allowed sediment accretion to keep pace with rising sea levels. A mid- to late-Holocene record of intertidal conditions preserved in the Delta indicates that slowing of relative sea-level rise allowed net accumulation of sediment in the Delta (Atwater et al., 1979; Atwater and Belknap, 1980; Orr et al., 2003). During this time, sediment supply was sufficient for deposition to keep pace with accommodation space formation, to preserve equilibrium marsh plain elevations at about MHHW over the long-term.

2.3 Landscape Characteristics Before Euro-American Settlement

2.3.1 Morphology and Habitat Areas

The morphology of the Delta before Euro-American settlement is shown in Figure 2. There was approximately 350,000 acres of freshwater tidal marsh plain at approximately MHHW. This marsh plain was predominantly vegetated by tule (Bay Institute, 1998). The tidal marsh was drained by a system of tidal and distributary channels, comprising about 27,000 acres. Each tidal channel had a tidal ‘watershed’, the marsh area that each channel fills and drains, and whose scale dictated the channel size and drainage density of the tidal channel system downstream.

In addition there were about 23,000 acres of supratidal natural levees of the Sacramento Delta that extended into the tidal marsh (Bay Institute, 1998). This higher ground supported a riparian woodland community of willows, alder, and oak.

2.3.2 Morphometry

Because the historic tidal marsh and channel system had evolved in equilibrium with sedimentation and peat formation balancing sea-level rise, it is possible to construct a hypsometry for the historic Delta as shown in Figure 3 (the hypsometry is the measurement of land area relative to sea level). This hypsometric curve uses the areas mapped as marsh plain and channel shown in Figure 2. A typical maximum channel depth of about 48 ft below MLLW (or 46 ft below NAVD) for the largest tidal channel was obtained from early hydrographic surveys. In the absence of a more detailed hydrography of the historic Delta, the subtidal morphometry was assumed to be a straight line interpolation between zero area at -46 ft and 27,000 acres at +6 ft NAVD. With this construction we estimate that the historic tidal volume of the Delta was approximately 700,000 acre-ft and the tidal prism was approximately 100,000 acre-ft assuming an average diurnal tidal range of approximately 4.0 ft. The tidal range is based on NOAA tide data for the modern Delta that shows MLLW is on average approximately 2.0 ft above NAVD and MHHW is approximately 6.0 ft above NAVD.

2.3.3 Active Accommodation Space

One of the primary adjustments available to the Delta landscape is change in sediment storage. The term ‘active accommodation space’ refers to the space available to store sediment under relative sea-level rise, or the volume difference between the existing sediment surface and the sediment surface that would evolve given sufficient sediment supply and time under modified boundary conditions. The ‘top’ surface of the active accommodation space created by relative sea-level rise represents a potential surface that the system will tend towards through the accumulation of sediment. Because of the dominance of relative sea-level rise in the present Delta landscape, the potential surface will always be above the existing surface, and therefore accommodation space will be positive.

In the 150 years prior to human intervention with sea level rise of approximately 2mm/yr, approximately 350,000 acre-ft of accommodation space was created in the Delta. Sedimentation and peat formation in tidal marshes filled all of this space as it was created, forming a wetland landscape in equilibrium with the processes that sustained it.

2.3.4 Stratigraphy

The contemporary sediments of the modern Delta are the culmination of Holocene sedimentation that began approximately 6,000 years ago. The Delta has filled with these sediments in response to sea-level rise and natural marine, estuarine and freshwater processes. The sediments are therefore characterized by complex lateral and vertical lithologic changes comprising alternations of inorganic sediments and peat which contain a record of the geomorphologic, climatic and sea-level evolution of the area. Although complicated in detail, the general stratigraphy of the Delta sedimentary succession can be broken down into four main units (Figure 4). These are, from the oldest to the youngest:

- Dense becoming loose sand
- Organic silt and clay
- Peat
- Channel deposits (silt and sand)

The lowermost unit comprises dense sand becoming loose towards the top of the unit. The sand unit represents deposition across the alluvial floodplain and is generally persistent across the Delta. Widespread units of organic silt and clay deposited in the incipient brackish marshes followed by peat formed in the freshwater tidal marshes overlying the sand. The silt and clay are up to 20 ft thick in the central Delta. The present peat layer is thickest in the west and central Delta (up to 30 ft thick) thinning to the north and south. Cutting through the silt-clay and peat deposits are a series of channel and natural levee deposits comprised of silt and/or sand upon which many of the artificial levees are constructed. It is likely that there is little peat preserved beneath the modern channels; it has either been eroded by channel scour or was never deposited.

2.4 Historic Changes in the Landscape

2.4.1 Levee Construction and Land Reclamation

Over the last 150 years, the natural landscape elements of the Delta have been transformed by human activities. The large freshwater tidal marsh of the Delta has been converted by levee building into a highly dissected region of channels and leveed islands used for agriculture (Simenstad et al., 2000). Today, the Delta contains over 55 ‘dry’ islands or tracts that are protected from flooding by more than 1100 miles of levees (Figure 5). Only a few examples of relatively pristine tidal marsh still exist such as Browns Island and on narrow bands of emergent vegetation located between the channels and levees. These marshes amount to less than 2% of the historic marsh. Much of the natural riparian vegetation bordering distributary channels has also been lost. In general, levees were constructed either along firmer ground on the natural levees of distributary channels or along the edge of the larger natural tidal channels.

2.4.2 Channelization and Dredging

As the tidal marsh was reclaimed, the natural tidal and distributary channel system was extensively modified to provide for navigable access to farms and by excavation to build up levees. The result was the creation of a series of leveed agricultural islands separated by a network of artificial channels through which the freshwater flows from the Sacramento and San Joaquin Rivers are conveyed. Some of the channels have been deepened and straightened by dredging either for shipping or for more efficient water transfer.

The main Delta channels have been widened, dredged, and straightened to allow for passage of ships. Dredging of the Sacramento River Deep Water Ship Channel (SRDWSC) makes it navigable for ocean-going ships as far inland as Sacramento (Figure 5). Cache Slough is also dredged as it forms part of the SRDWSC. Along the San Joaquin River, the dredged Stockton Deep Water Ship Channel (SDWSC) makes the lower reach of the river navigable for ocean shipping as far inland as Stockton. At Stockton, there is an abrupt change in channel geometry from a deep channel downstream to a shallow river channel upstream.

2.4.3 Abandoned Flooded Islands

The levees on several former Delta islands have failed and have not been repaired over the last 80 years, converting them to open water with varying degrees of connection to the surrounding channels. These large subtidal areas would not have existed in the pre-settlement Delta. The main abandoned islands are Liberty Island and Little Holland Tract adjacent to Cache Slough in the northern Delta, and Lower Sherman Lake, Big Break, Franks Tract, and Mildred Island adjacent to the San Joaquin River in the west-central Delta (Figure 5).

Once an island is permanently flooded the newly formed open water becomes part of the volume of water subject to tidal exchange within the Delta. At a landscape scale, each abandoned island contributes incrementally to the total tidal prism of the Delta and becomes a potential sink for sediment introduced from the adjacent channel. In addition, these new areas of open water are susceptible to the influence of wind-generated waves, through creation of longer wind fetches.

2.5 Historic Changes in the Processes Affecting Landscape

2.5.1 Subsidence and Relative Sea-level Rise

The process of land reclamation followed by island drainage, decomposition of organic carbon in the peat soils, erosion, and consolidation has caused widespread subsidence of the former marsh surface that continues today (DWR, 1995; Deverel and Rojstaczer, 1996; Deverel et al., 1998; Ingebritsen and Ikehara, 1999). Island surfaces in the west and central Delta have subsided from their original elevation of around MHHW to their present elevations that can be more than 20 ft below MHHW.

The dominant cause of land subsidence in the Delta is decomposition of organic carbon in the peat soils (Ingebritsen and Ikehara, 1999). Prior to agricultural development, the soil was waterlogged and anaerobic (devoid of oxygen) and organic carbon accumulated faster than it could decompose. Drainage for agriculture led to aerobic (oxygen-rich) conditions that favor rapid microbial oxidation of the carbon in the peat soil. Most of the carbon loss is emitted as carbon-dioxide gas to the atmosphere. In certain areas, groundwater extraction and gas field pumping can also contribute to local and regional subsidence.

The principle control on the magnitude of subsidence is the composition of the marsh soils. At a landscape scale, the soils of the central Delta, which are generally more organic rich, exhibited the highest average historic rates of subsidence, between 0.10 and 0.16 ft/yr (Mount and Twiss, 2005). The more inorganic soils of the northern Delta exhibited lower rates of subsidence. On a local scale, the surface profile of individual islands is generally ‘saucer-shaped’, because subsidence is greater in the peat soils near the interior than in the more inorganic rich soils near the perimeter.

Over time, the lower elevations caused by soil subsidence were exacerbated by relative sea-level rise. This has had a significant impact on the stability of the Delta levees by gradually increasing the difference in head between the water surface of the Delta channels and the interior of the islands.

The few remaining natural and restored tidal marshes in the Delta are sustained primarily by the accumulation of organic rich soils derived from surface vegetation growth. Orr et al. (2003) summarized marsh accretion across the Delta and considered that rates of 0.03-0.06 ft/yr to be representative. These accretion rates, if sustained in the future, would be sufficient to keep pace with predicted relative sea-level rise and allow the marsh surfaces to maintain their elevation within the tidal frame.

2.5.2 Wind Waves

Locally-generated wind waves in abandoned flooded Delta islands can lead to erosion of levees protecting other Delta islands from flooding. Levees may be weakened by this erosion resulting in levee conditions that are more susceptible to failure and breaching during storm events. Across much of the Delta wind fetches that are needed to generate high waves are limited by the physical layout and scale of the flooded islands. Over time, the lengths of wind fetches will most likely increase and create opportunities for larger wind waves and erosive forces to develop. In addition, wind fetches could also increase in future years due to continued relative sea-level rise and levee erosion.

2.5.3 Sediment Budget

In the upstream watershed major changes in sediment budget occurred after the 1849 gold rush (Gilbert, 1917). By 1880, a combination of overgrazing, deforestation, floodplain reclamation and, most importantly, hydraulic mining caused huge increases in the amounts of sediment delivered to the Delta. Since active accommodation space was limited within the Delta, the bulk of this mining sediment bypassed the region, eventually accumulating in Suisun and San Pablo Bays. Hydraulic mining operations largely ceased in 1884 and sediment discharge gradually reduced as a consequence. Shvidchenko et al. (2004) showed that from the 1880s to the end of the 20th century, the sediment supply to the Delta declined by approximately 75% (Table 2-1). They also reported a reduction in supply to Suisun Bay from the Delta of approximately 90%.

Table 2-1
Historic Sediment Budgets for the Delta (Shvidchenko et al., 2004)

Supply ($Mtyr^{-1}$)	1849-1885	1960-1990	End 20th Century
Delta Inflow	17.0	4.0-5.3	3.9
Delta Deposition	4.0	0.6-1.9	1.8
Dredged	0		0.9
Water Diversion Export	0	0.2-1.1	0.8
Outflow to Suisun Bay	13.0	2.6-3.6	1.3

Wright and Schoellhamer (2004) attributed the reduction in sediment supply to anthropogenic changes in the Central Valley watersheds. Before colonization, the watersheds were largely undisturbed, floodplains were intact, and sediment discharge to the Delta was relatively low. Alluvial sediment entering the Delta was deposited on the marsh plains, allowing their surface elevations to keep pace with sea-level rise. The balance changed in the 20th century with the closure of hydraulic mining and the construction of dams and reservoirs across rivers in the Sierra Nevada foothills that capture sediment and reduce flood flows. Levees were constructed that eliminated the natural marshes that acted as sediment sinks (Wright and Schoellhamer, 2004) and it is likely that much of the sediment that now enters the Delta (including remnants of the 19th century hydraulic mining debris) is captured by breached and flooded islands immediately adjacent to the Sacramento River (Reed, 2002). Away from the main channels, the west-central Delta deeply-subsided flooded islands, such as Lower Sherman Lake, Big Break, and Franks Tract, are receiving very limited supplies of sediment (Simenstad et al., 2000; Orr et al., 2003). Sedimentation rates are low in part because high wind-fetch conditions generate waves and currents that resuspend deposited sediments.

At a landscape scale, dredging of the main channels of the Sacramento and San Joaquin Rivers also affected the sediment budgets of the Delta and Suisun Bay. Shvidchenko et al. (2004) estimated that as of year 2000 approximately 900,000 tons of sediment is removed from the Delta on an annual basis for navigation and levee maintenance purposes.

3. Present State of the Delta

3.1 Morphometry and Habitat

The morphometry of the modern Delta is calculated by using USGS bathymetric data consisting of an integer grid of water depth developed from a database of point soundings from multiple existing data sources post-1980. The grid has a cell size of 10 meters and elevations are in tenths of a foot relative to NGVD 29.

The resulting hypsometry constructed from the USGS data is shown in Figure 6. It can be seen that compared to the historic Delta the area of open water and tidal volume has approximately doubled due in large part to the abandonment of flooded islands, and also due to dredging of navigation channels. Breaching of these islands has provided the Delta with approximately 17,000 acres of extra open-water area, with depths up to approximately 20 ft below MHHW. This equates to additional tidal volume of approximately 160,000 acre-ft. To date the abandoned flooded islands have added potential diurnal tidal prism of approximately 60,000 acre-ft. The potential diurnal tidal prism is the volume between the planes of MHHW and MLLW above a particular location in the estuary. The actual diurnal tidal prism, the average volume of water ebbing and flooding on a daily tidal cycle, is affected by the particular hydrodynamics of the estuary and is less than the potential tidal prism.

Flooded islands provide poor quality habitat for native aquatic plant and animal communities, in part because they allow the growth of extensive stands of non-native submerged aquatic vegetation (SAV) (Simenstad et al., 2000; Orr et al., 2003). The abandoned levee breaches on subsided lands have resulted primarily in the creation of subtidal open water perhaps with a fringe of emergent vegetation along the levee edge (Orr et al., 2003). Because of low sedimentation rates, even on shallow subsided sites breached 80 years ago in the west and central Delta, wind-wave action has prevented sedimentation and marsh re-establishment.

About 98% of the historic freshwater tidal marsh in the Delta has been eliminated. In addition much of the riparian woodland that colonized the natural levees along distributary channels has been eliminated by levee construction or bank rip-rapping.

3.2 Potential Accommodation Space

The construction of levees and consequent land subsidence has fundamentally altered the Delta landscape by the creation of a large potential accommodation space volume below MHHW filled neither with sediment nor water. The potential accommodation space differs from the active accommodation space in that the former is diked and therefore cannot accumulate sediment, whereas the active accommodation space is filled with water through which sediment can be deposited on to the substrate.

We estimated this potential accommodation space by using Interferometric Synthetic Aperture Radar (IfSAR) mapping undertaken by the U.S. Army Corps of Engineers. The IfSAR data was flown in 1997 and 1998 and was obtained in the form of a DEM which covers the topography of the legal Delta, has a grid cell size of ten meters with elevations in meters NAVD to the ten thousandths.

The hypsometry of the Delta constructed from the IfSAR data shows a large unfilled volume below MHHW of the order of 3.5 million acre-ft as shown in Figure 6. The potential accommodation space created to date is therefore three times the current tidal volume of the Delta channels and flooded islands and approximately 45% of the total volume of the existing San Francisco Bay-estuary (approximately 7.7 million acre-ft, Williams, 1989).

This estimate of potential accommodation space is substantially larger than the approximately 2.0 million acre-ft estimated by Mount and Twiss (2005) (see their Figure 5a). There appears to be several reasons for this difference:

1. Our definition of potential accommodation space is the volume below MHHW (the elevation of the natural marsh plain) instead of mean sea level (MSL), as used by Mount and Twiss (2005).
2. The project area size used by Mount and Twiss (2005) is smaller than our project area, which extends to the legal boundary of the Delta.
3. Mount and Twiss (2005) used an average elevation for each island.
4. Mount and Twiss (2005) start their potential accommodation space calculations at year 1900 and hence some of the islands would already have subsided.

4. The Future Landscape

4.1 Processes Affecting Future Landscape Change

4.1.1 Global Sea-level Rise

It is anticipated that future climate change will accelerate global (eustatic) sea-level rise. Recent estimates for different greenhouse gas emission scenarios range from 0.4 to 2.4 ft by 2100, with mid level estimates of between 0.85 and 1.28 ft by 2100 (Cayan et al., 2006). IPCC (2007) predicted global average sea-level rise between 1980/1999 and 2090/2099 of between 0.59 and 1.94 ft. For this analysis we have assumed that global sea-level rise will be 1 foot over the next 100 years.

The DRMS Climate Change TM provided recommendations for a range of mean sea-level rise values to be considered by the DRMS project. These values are 0.7, 1.6, 3.0, and 4.6 ft by 2100. This range of values is generally higher than the mid-level estimates of Cayan et al. (2006) and IPCC (2007) and indicates that there are considerable uncertainties in the estimation of future global sea-level rise. We have evaluated the significance of these uncertainties by examining how a higher sea-level rise estimate of 3 ft over the next 100 years may affect the future landscape.

4.1.2 Soil Subsidence

Rates of subsidence on the Delta islands have declined since the 1950s due to improved land-use practices (Deverel and Rojstaczer, 1996; Deverel et al., 1998). Further subsidence is also constrained by the thickness of organic-rich sediments deposited during the mid- to late-Holocene. In the south and east Delta, historic subsidence has reduced or eliminated the organic rich soils, whereas the thicker organic soils of the central and west Delta continue to subside. Mount and Twiss (2005) found that post-1950 subsidence rates were 20–40% less than the average rate between 1925 and 1981. We have assumed that the future rate of subsidence of the leveed islands, historically about 0.10 to 0.16 ft/year, will slow by 40% over the next 100 years, to approximately 0.06 to 0.09 ft/year (average 0.08 ft/year or 7.9 ft over 100 years).

The DRMS Subsidence TM provided estimates of island subsidence by 2100. These estimates predicted subsidence of 8.4 to 9.6 ft for large areas of the central Delta, generally decreasing to 0 to 1 ft towards the legal boundary. Although an estimate for average subsidence across the whole Delta was not provided, it is likely to be lower than the value we calculated using Mount and Twiss (2005) assumptions, highlighting the uncertainty in the prediction. We have evaluated the significance of this uncertainty by examining how a lower subsidence of 4 ft over the next 100 years may affect the future landscape.

4.1.3 Sediment Budget and Dynamics

Shvidchenko et al. (2004) suggested that if trends continue, the average sediment input to the Delta will likely decline to about three million tons per year in the next few decades and sediment output from the Delta and sediment deposition in the Delta will both reduce to about one million tons per year assuming water export operations remain at the same level with the loss of approximately one million tons per year of sediment to diversions. We have assumed that this lower rate of sediment supply to the Delta will continue over the next 100 years, amounting to total sediment deposition of approximately 100 million tons or approximately 90,000 acre-ft. We test the significance of changes in sediment deposition on the future landscape by examining the impact of a higher rate of sediment supply, equivalent to 3 million tons or approximately 270,000 acre-ft.

4.1.4 Vegetation Colonization

Simenstad et al. (2000) found that pioneer marsh vegetation in breached-levee sites establishes rapidly (within approximately four years) at a median elevation of around 3.3 ft MLLW (range 1.3 to 4.9 ft MLLW). Once established, vegetation spreads to lower elevations (median -1.0 ft MLLW) by lateral expansion from the initial patches. Lateral expansion proceeds at a slow rate (maximum of 4.9-9.8 $ftyr^{-1}$) and requires sheltered, low wave energy conditions. Once vegetation is established it can keep pace with high rates of relative sea-level rise (Orr et al., 2003), building up peat soils.

4.2 Conceptual Model of Future Evolution of the Delta

To analyze the potential future morphometry of the Delta over the next 100 years, we have made the following assumptions:

- For islands whose levees are always maintained and repaired, land subsidence will continue at the declining rates projected by Mount and Twiss (2005). This means that potential accommodation space continues to increase within the Delta. Sea-level rise causes only minor increases in tidal volume and tidal prism in areas between levees.
- Where levees fail and islands are abandoned, the potential accommodation space becomes active tidal volume, and the tidal prism will increase in proportion to the new tidally influenced area.

- Where islands are abandoned, we assume all sediment delivered to the Delta is captured in the flooded islands reducing tidal volume. This is an overly conservative assumption but because sediment delivery is small relative to flooded island volume it is not a significant term.
- Where islands are abandoned, tules will vegetate to approximately one foot below MLLW rapidly forming peat deposits that occupy a portion of the tidal volume and tidal prism of the flooded island.
- Where islands are abandoned the increased tidal prism will induce channel deepening.

Figure 7 illustrates how we understand these processes would affect Delta morphometry.

4.3 Potential Scenarios

For simplicity, we have analyzed three extreme 'book end' scenarios to bound the range of possible outcomes. These are:

- The 'business as usual' scenario where the levees are maintained and remain intact in their present configuration indefinitely.
- Complete levee failure and island abandonment at year zero, followed by morphologic evolution over the next 100 years.
- The 'business as usual' scenario for the next 100 years followed by complete levee failure and island abandonment.

4.3.1 'Business as Usual'

If the levees are maintained and remain intact for the next 100 years then the dominant process controlling morphologic change in the Delta is the predicted relative sea-level rise of approximately one foot (Cayan et al., 2006). The leveed islands will be subject to continued soil subsidence at an average rate of approximately 0.08 ft/year or 7.9 ft in 100 years. We have assumed that very little sedimentation takes place in the Delta channels and abandoned islands but sedimentation on remnant and existing tidal marshes keeps pace with future relative sea-level rise (Simenstad et al., 2000, Reed, 2002; Orr et al., 2003).

4.3.2 Total Levee Failure at Year Zero

Under a scenario where all the Delta levees fail at year zero, the hypsometry in 100 years will change as determined by relative sea-level rise (1 foot in 100 years), sedimentation rates in the newly-created subtidal open-water system and fringing intertidal areas, and scouring of channels caused by the increase in upstream tidal prism.

The large open-water and intertidal area would become a potential new sink for sediment introduced from the Central Valley watershed. We have calculated an average accretion of 0.25 ft over 100 years using a depositional mass of 1 million tons (Shvidchenko et al., 2004) spread over the area of the Delta (excluding channels) that would be become inundated should all the levees fail. This value is likely to be an overestimate in the subtidal areas because the high wind-fetch conditions created by the large expanse of water would tend to keep sediment particles in suspension decreasing sedimentation rates.

Approximately 80,000 acres of the current Delta are high enough to colonize as freshwater tidal marsh and we assume that peat formation will occupy a portion of the tidal volume.

If all the levees failed at year zero, the large increase in tidal prism would cause downstream channels to scour increasing the tidal volume. Eventually, the channel cross-section equilibrates to the new tidal prism. The relationship between tidal prism and equilibrium channel cross-sectional area in the Delta is illustrated in Figure 8 for natural and restored tidal marsh sites in the Delta (Simenstad et al., 2000). Based on these hydraulic geometry relationships, we have increased channel depths below approximately MLLW by a factor of 1.4.

4.3.3 Total Levee Failure at Year 100

Under a scenario where the levees remain intact for the next 100 years then totally fail at year 100, the farmed islands in the Delta prior to failure would be subject to the same subsidence processes as the 'business as usual' scenario, with increasing potential accommodation space.

4.4 Results

Figures 9, 10, and 11 show the changes in hypsometry from historic conditions to potential future scenarios. Table 4-1 summarizes the key metrics obtained from this analysis.

Table 4-1 Potential Morphometric Characteristics of the Evolving Delta

Scenario	Date	Potential Tidally Influenced Area (acres)			Potential Tidal Volume below MHHW (Million acre-ft)	Potential Diurnal Tidal Prism (Million acre-ft)	Active Accommodation Space (Million acre-ft)	Potential Accommodation Space (Million acre-ft)
		Subtidal	Intertidal	Total				
Historic Delta	~1850	27,000	350,000	377,000	0.7	0.1	0	0
Modern Delta	Year 0	54,500	4,000	58,500	1.2	0.2	0.5	3.5
Modern Delta (levees intact)	Year 100	55,000	4,000	59,000	1.3	0.2	0.6	7.0
Complete Levee Failure at T+0	Year 0	297,000	80,000	376,000	4.7	1.3	4.0	0
Complete Levee Failure at T+0	Year 100	307,000	85,000	392,000	4.9	1.4	4.2	0
Complete Levee Failure at T+100	Year 100	466,000	68,000	534,000	8.3	2.0	7.6	0

We have used these estimates to calculate potential future habitat areas for each of the selected scenarios.

4.4.1 ‘Business as Usual’

Under the ‘business as usual’ scenario, a relative sea-level rise of one foot would result in a relatively small increase in the tidally-influenced area from 58,500 to 59,000 acres. Of this area, approximately 4,000 acres would be intertidal. We anticipate that sediment supply to the intertidal surface will be sufficient to keep pace with relative sea-level rise and that expansion of marsh vegetation would take place rapidly (Simenstad et al., 2000) to cover much of the existing 4000-acre intertidal zone, and potentially colonize down to elevations 1 foot below MLLW. Under this scenario the tidal volume would increase from approximately 1.2 million acre-ft to 1.3 million acre-ft and the tidal prism would be similar to the year zero tidal prism (Figure 9 and Table 4-1).

4.4.2 Total Levee Failure at Year Zero

Under the total levee failure at year zero scenario, the deeply subsided flooded islands would accumulate sediments very slowly, under the influence of relative sea-level rise, and would persist in a flooded state. However, parts of the Delta system may attain elevations critical for tule growth potentially supporting a transition back to the former marsh plain state (Orr et al., 2003). Over the succeeding 100 years, we have assumed that in wave-sheltered intertidal areas sediment supply is sufficient to allow sediment accretion to keep pace with sea-level rise. Hence, depending on exposure to wind-waves, the vegetated area may expand laterally to cover much of the intertidal area equating to less than 5% of the existing accommodation space.

Under this scenario the tidal volume at year 100 would be approximately 4.9 million acre-ft and the potential diurnal tidal prism would be approximately 1.4 million acre-ft (Figure 10 and Table 4-1). The large increase in tidal prism could cause major channel scouring throughout the Delta. For example, extrapolating from the hydraulic geometry relationship of Figure 8, the current cross-sectional area of the San Joaquin River at Antioch would be predicted to expand from approximately 70,000 to about 250,000 square ft.

4.4.3 Total Levee Failure at Year 100

Under this scenario the potential accommodation space behind the levees would be substantially larger than at present, increasing to 7.0 million acre-ft. Figure 11 and Table 4-1 show the changes in tidal volume and tidal prism. Approximately 70,000 acres would remain shallow enough to be colonized by marsh vegetation.

4.4.4 Sensitivity Analysis

Considerable uncertainties exist in the estimation of the main factors affecting landscape-scale change (global sea-level rise, soil subsidence, and sediment supply). The significance of these uncertainties can be tested by examining how a range of possible values or different assumptions would affect the future landscape under each of the three potential scenarios. The following are the factors tested for significance:

1. Increase global sea-level rise to 3 ft by year 100, reflecting the variability of recent estimates of the Climate Change TM, IPCC (2007) and Cayan et al. (2006).
2. Reduce average soil subsidence to 4 ft by year 100 to account for lower average subsidence values discussed in the Subsidence TM.
3. Increase sediment deposition in the Delta to 3 million tons over the next 100 years to reflect higher sediment delivery due to potential long-term climatic variability.

Table 4.2 illustrates how altering each independent variable (sea-level rise, subsidence, and sedimentation) affects the primary dependent variables (tidally-influenced area, tidal volume, tidal prism, and accommodation space).

Table 4-2 Sensitivity Analysis

Scenario	Sensitivity Parameter	Date	Potential Tidally Influenced Area (acres)			Potential Tidal Volume below MHHW (Million acre-ft)	Potential Diurnal Tidal Prism (Million acre-ft)	Active Accommodation Space (Million acre-ft)	Potential Accommodation Space (Million acre-ft)
			Subtidal	Intertidal	Total				
Historic Delta		~1850	27,000	350,000	377,000	0.7	0.1	0	0
Modern Delta		Year 0	54,500	4,000	58,500	1.2	0.2	0.5	3.5
Modern Delta (levees intact)	Initial Est.	Year 100	55,000	4,000	59,000	1.3	0.2	0.6	7.0
	Sea-Level		56,500	4,000	60,500	1.4	0.2	0.7	8.0
	Subsidence		Unchanged – assumed no subsidence in Delta channels						
	Sediment		Unchanged – assumed no sedimentation in Delta channels						
Complete Levee Failure at T+0	Initial Est.	Year 100	307,000	85,000	392,000	4.9	1.4	4.2	0
	Sea-Level		347,000	80,000	427,000	5.8	1.5	5.1	0
	Subsidence		Unchanged – subsidence assumed to cease upon failure						
	Sediment		300,000	81,000	381,000	4.8	1.4	4.1	0
Complete Levee Failure at T+100	Initial Est.	Year 100	466,000	68,000	534,000	8.3	2.0	7.6	0
	Sea-Level		509,000	48,000	557,000	9.4	2.1	8.7	0
	Subsidence		394,000	76,000	470,000	6.6	1.7	5.9	0
	Sediment		Unchanged – assumed no sedimentation in Delta channels/islands						

Increasing global sea-level rise by 200% has minimal impacts on the outcome of the 'business as usual' (levees intact) scenario. However, by year 100 the potential tidally influenced area incrementally increases by approximately 9% (35,000 acres) and 4% (23,000 acres) in the total failure of the levees at year zero and year 100 scenarios, respectively. Although the total tidally influenced area increases in both of these scenarios, the potential intertidal area incrementally decreases by between 6% (5,000 acres - failure at year zero) and 29% (20,000 acres - failure at year 100). Potential tidal volume and tidal prism in year 100 incrementally increase by 13–18% (approximately 1.0 million acre-ft) and 5–7% (0.1 million acre-ft) respectively, for the levee failure scenarios.

Decreasing subsidence by 50% has little influence on the outcomes of the 'business as usual' and the complete levee failure at year zero scenarios because we have assumed no subsidence beneath inundated areas. However, subsidence has a significant impact if the levees fail at year 100. In this scenario, the potential intertidal area incrementally increases by approximately 12% (8,000 acres), with an incremental loss of approximately 12% (64,000 acres) of the total tidally influenced area. The tidal volume incrementally decreases by 20% (1.7 million acre-ft) and the tidal prism decreases by 15% (0.3 million acre-ft).

Increasing sediment deposition by 200% has little influence on the outcomes of the 'business as usual' and the complete levee failure at year 100 scenarios because we have assumed no sedimentation in the Delta channels. Sedimentation impacts the tidal characteristics at year 100 only when the levees fail at year zero. In this scenario, the tidally influenced area and intertidal areas incrementally decrease by 12% (11,000 acres) and 5% (4,000 acres), respectively. The change in sedimentation has minimal impact on the volumetric tidal characteristics.

5. Conclusions

1. Over the last 5,000 years freshwater tidal marshes in the Delta kept pace vertically with gradually rising sea level (1-2 $mmyr^{-1}$) at approximately MHHW elevation by building up peat and peaty mud through sediment deposition and biomass accumulation.
2. With rising sea level these marshes grew laterally into the Central Valley occupying approximately 350,000 acres at the time of European colonization. This constituted the most extensive contiguous freshwater tidal marsh system on the west coast of North America.
3. There were no extensive intertidal mudflats or sandflats within the Delta because freshwater marsh vegetation can colonize to below the low tide line. This meant there were no extensive open water areas with large wind fetches in the historic Delta similar to Suisun Bay.
4. The historic marshes were drained by a dendritic tidal channel system whose major sloughs merged upstream into the distributary channels of the Sacramento and San Joaquin Rivers. The shape of most of these tidal channels was dictated primarily by tidal rather than river flows.
5. In its pre-colonization state the morphology of the Delta was largely in equilibrium with the physical processes that sustained it; the tides, floods, the transport of sediment, and sea-level rise. Accommodation space was small and limited to the volume of annual sea-level rise. This meant that the morphometry of the Delta, including the tidal volume and tidal prism, only gradually changed as the San Francisco Bay-estuary expanded inland.

6. In its pre-colonization state, the diurnal tidal prism, the volume of the tides that flowed in and out of the Delta on an average daily tidal cycle, was quite limited for such an extensive estuarine system, and was determined almost entirely by the volume of water in the sinuous tidal channels that drained the marshes. Sediments discharged into the Delta during large floods on the Sacramento or San Joaquin Rivers would either be conveyed through the Delta to the Suisun Bay or captured within the tidal marsh.
7. Over the last 150 years, the natural geomorphic system of the Delta has been transformed by human activity; approximately 98% of the tidal marshes were converted to agricultural land by levee construction that converted the former marshes into individual leveed islands.
8. The land surfaces on many of the leveed islands have subsided up to 20 ft below MLLW over the last century. In this period sea level has risen by approximately 0.5 ft.
9. Approximately 17,000 acres of former leveed islands have been abandoned in the last 100 years. Because the abandoned island floors had subsided below the limit of colonization of marsh vegetation, large expanses of open water were formed, causing a significant increase in the total volume and tidal prism of the Delta.
10. In the last 100 years, the change in land surface elevation relative to the tidal frame on currently farmed land has created a large artificial empty space below MHHW, or potential accommodation space, of approximately 3.5 million acre-ft (significantly larger than previously estimated). This volume is approximately three times the existing volume of the Delta and 45% of the volume of the whole San Francisco Bay Estuary.
11. Over the next 100 years sediment deposition in to the Delta from the upstream river system is expected to decline to approximately 1.0 million tons per year. If all this sediment were captured in the Delta it could fill approximately 3% of the existing accommodation space created by human-induced land subsidence.
12. Over the next century average land surface subsidence rates are expected to continue but decline from an average of approximately 0.13 ft/yr to 0.08 ft/yr.
13. Over the next century sea-level rise is expected to accelerate with the average of the mid-level estimates predicting approximately 1.0 ft increase in sea-level.
14. If all the levees were maintained in their present configuration over the next 100 years (‘business as usual’) we expect the tidal prism to be similar to present (0.2 million acre-ft) and the tidal volume to increase from approximately 1.2 million acre-ft to 1.3 million acre-ft.
15. Under the ‘business as usual’ scenario, sediment supply to the intertidal surface would probably be sufficient to keep pace with relative sea-level rise and tidal marsh vegetation would likely spread laterally to cover approximately 4,000 acres.
16. Over the next century, assuming all existing levees are maintained intact, the combination of global sea-level rise (1 foot) and continued subsidence will

increase the potential accommodation space behind the levees to approximately 7.0 million acre-ft.

17. Under the scenario where all the levees fail and islands are abandoned in year zero, the tidal prism would be approximately 1.3 million acre-ft, and tidal volume would be approximately 4.7 million acre-ft. This would increase the potential tidal volume of the entire San Francisco Bay Estuary by 45%, and the potential diurnal tidal prism of the Delta would increase by approximately 500%.
18. Approximately 80,000 acres (about 20%) of the current area of the Delta is still high enough to be colonized by marsh vegetation in the event of levee failure and abandonment.
19. Over the succeeding 100 years sedimentation may fill wave sheltered areas, and depending on exposure to wind-wave action this might allow expansion of vegetated areas to cover the entire intertidal area. Assuming peat formation in vegetated marshes is rapid enough to allow marshes to grow vertically to MHHW approximately 5% of the accommodation space will be filled.
20. If all levees were to fail in year 100, approximately 70,000 acres of the Delta would remain intertidal, allowing colonization of marsh vegetation.
21. Any large increase in tidal prism due to extensive island abandonment would likely alter the hydrodynamics of the entire estuary, scouring tidal channels within the Delta and Suisun Bay.
22. Large scale island abandonment would create new large wind wave fetches that could limit vegetation establishment or erode established marshes and perimeter levees.
23. With large-scale island abandonment a larger proportion of sediment discharged to the estuary would be captured in the Delta. In addition, it is possible that a significant proportion of sediment now circulated off the mudflats and shallows in Suisun Bay could be captured in the Delta accelerating loss of mudflats and shoreline erosion in the estuary downstream.
24. Historic land subsidence has created irreversible changes in the geomorphic processes and landscape of the Delta, and any scenarios that contemplate extensive abandonment of Delta islands would cause major increases in tidal volume and tidal prism that would have large-scale impacts on the hydrodynamics, sediment dynamics, and salinity distribution of the entire estuary.
25. Changes to the dynamics of the estuary would significantly affect flood hazards, ecosystem processes, and water diversions. A portion of these impacts might be mitigated by selective island abandonment. For example, by appropriate analysis of the morphometry of the Delta, it is possible to identify which islands have the highest potential for recreating tidal marsh and minimizing increases in tidal prism.

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Figures

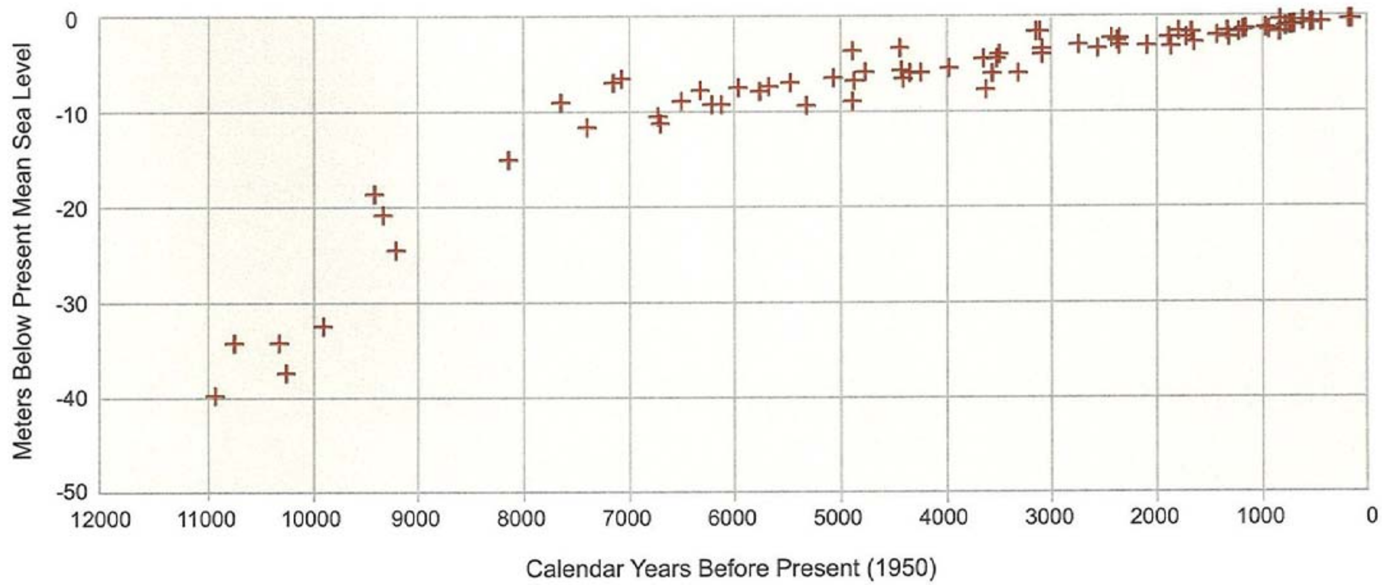

figure 1

DRMS Geomorphic Review

Holocene Relative Sea-Level Rise in San Francisco Bay

Source: Adapted from Meyer, 2003

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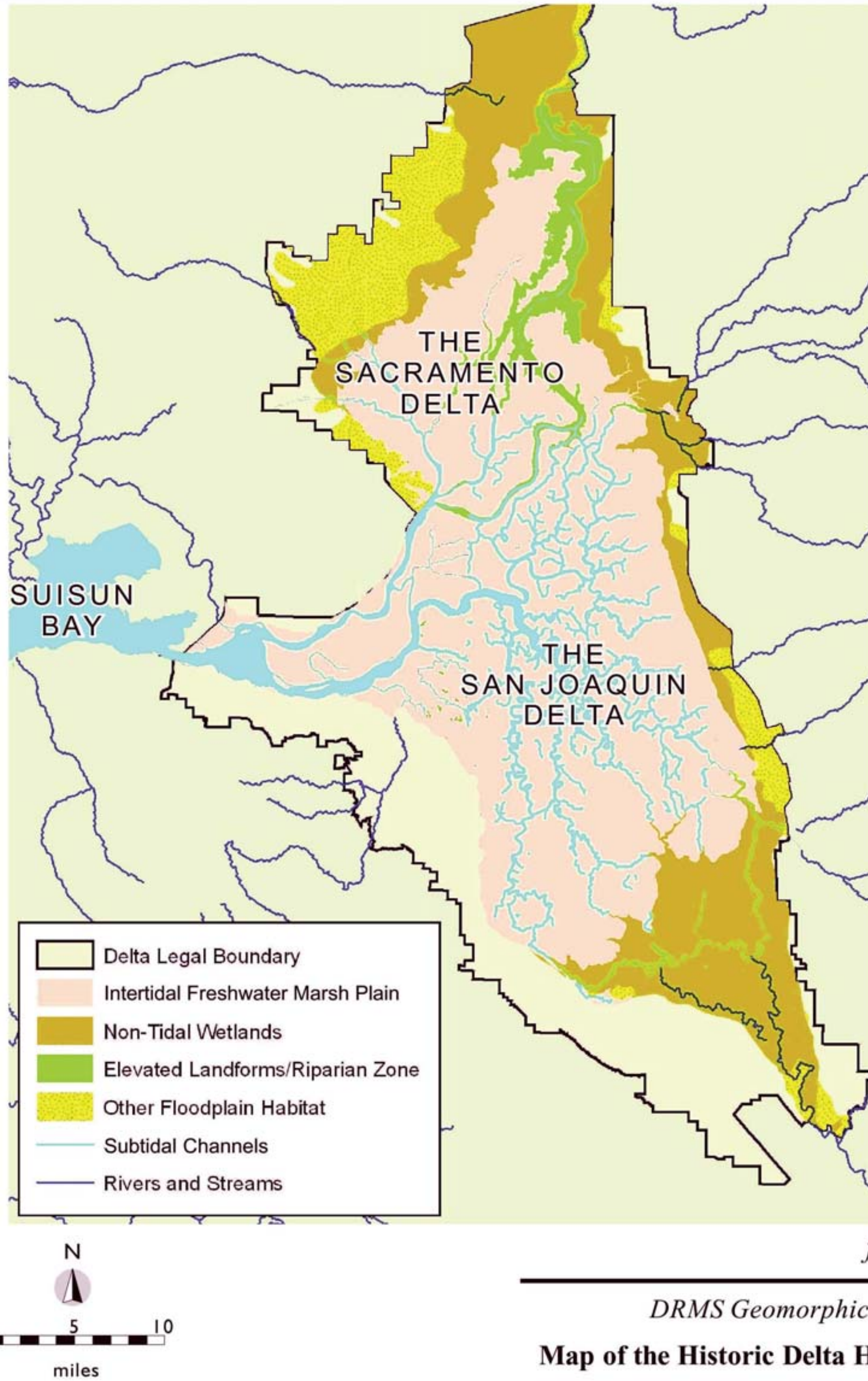

figure 2

DRMS Geomorphic Review

Map of the Historic Delta Habitats

Source: Bay Institute, 1998

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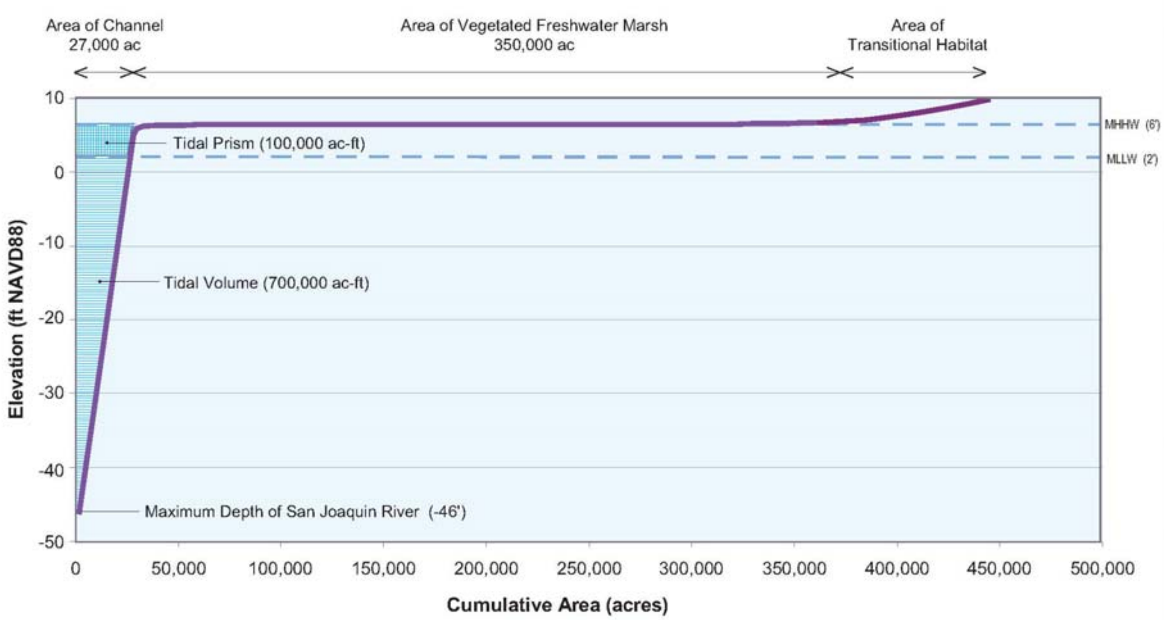

figure 3

DRMS Geomorphic Review

Reconstruction of Morphometry of the Historic Delta

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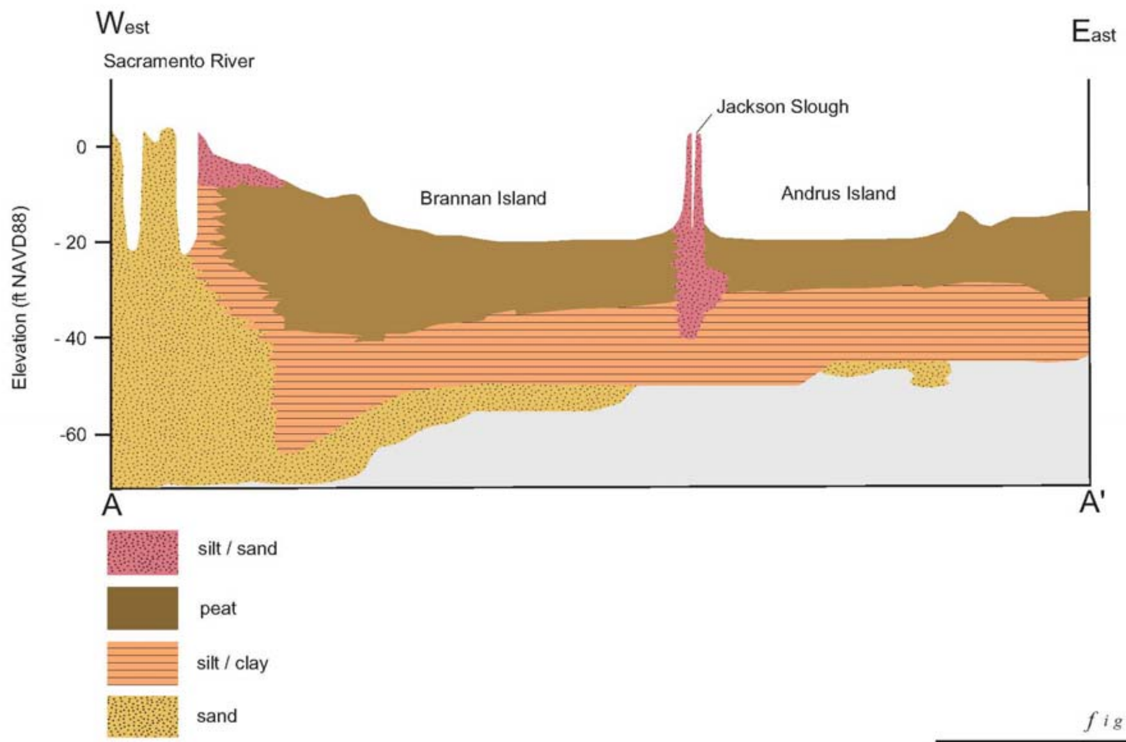

Location of section is shown on Figure 5

Note: The section is simplified and for clarity does not show any silt/sand units within the peat or silt/clay that may have been deposited by migrating channels.

Source: adapted from Atwater & Belknap, 1980

figure 4

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Delta Stratigraphy

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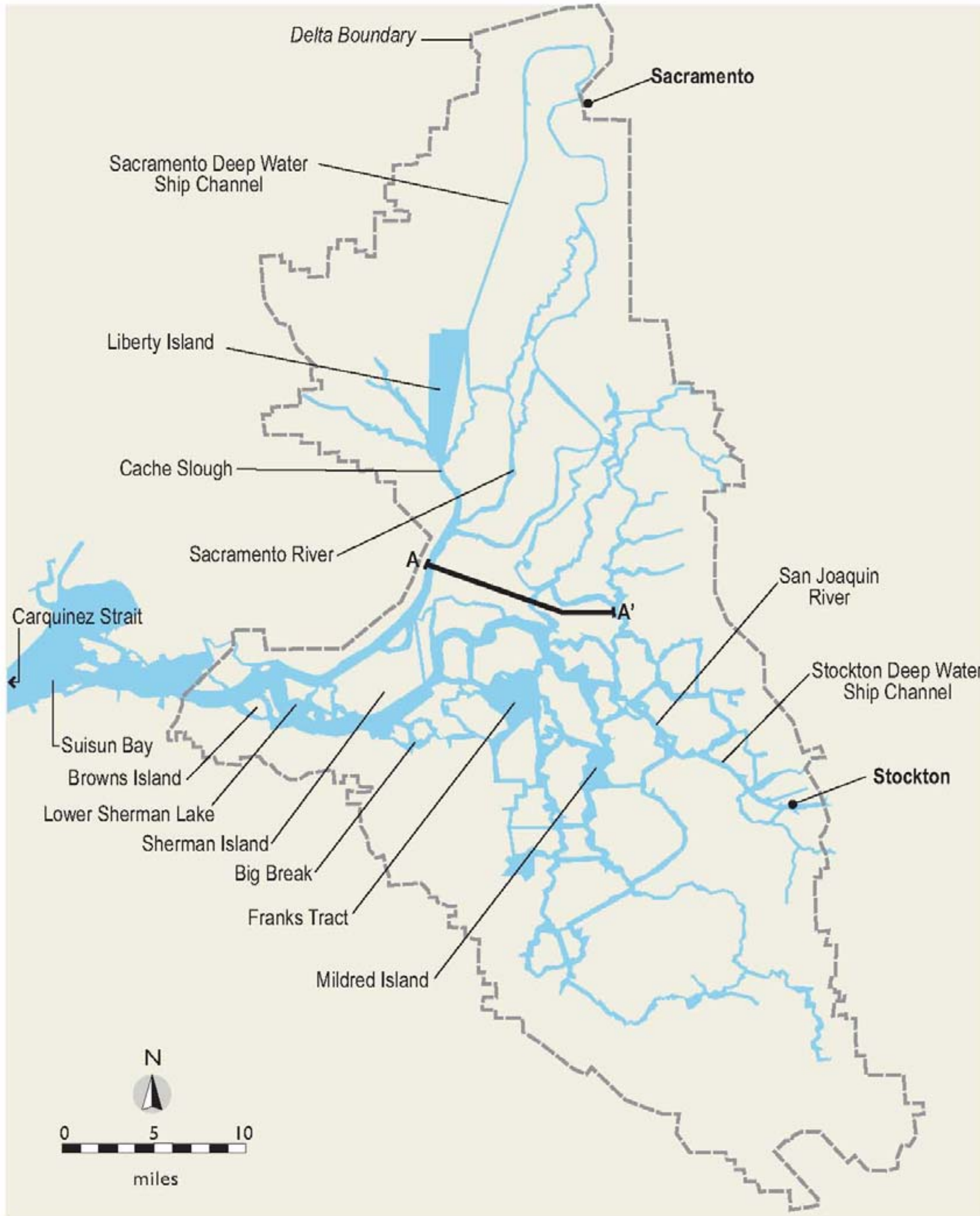

Section shown on Figure 4

figure 5

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Map of the Modern Delta

Source: DWR, 1995

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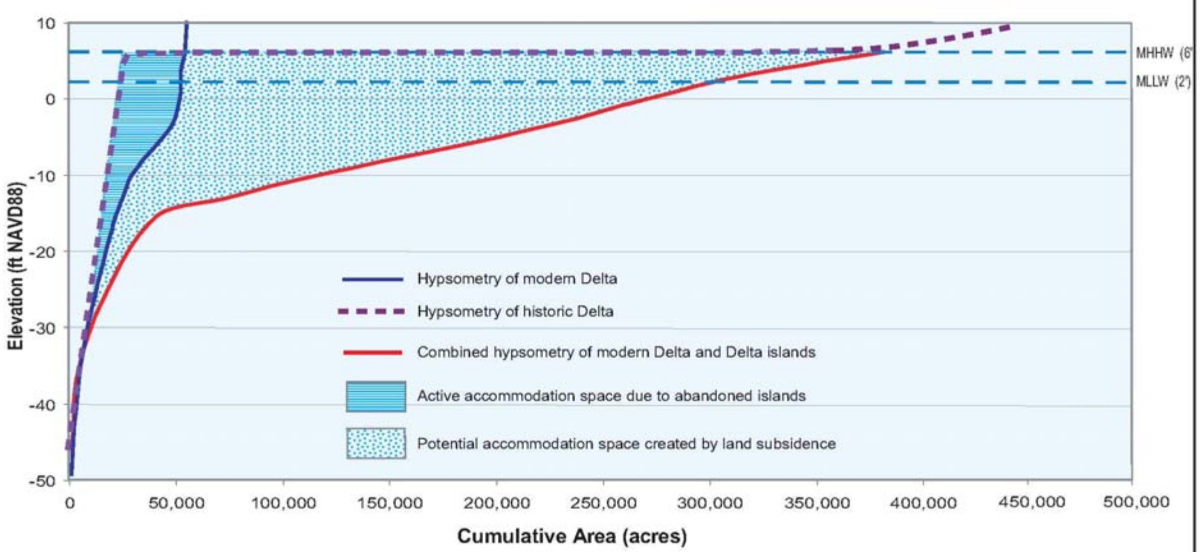

figure 6

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Potential Accommodation Space of the Modern Delta

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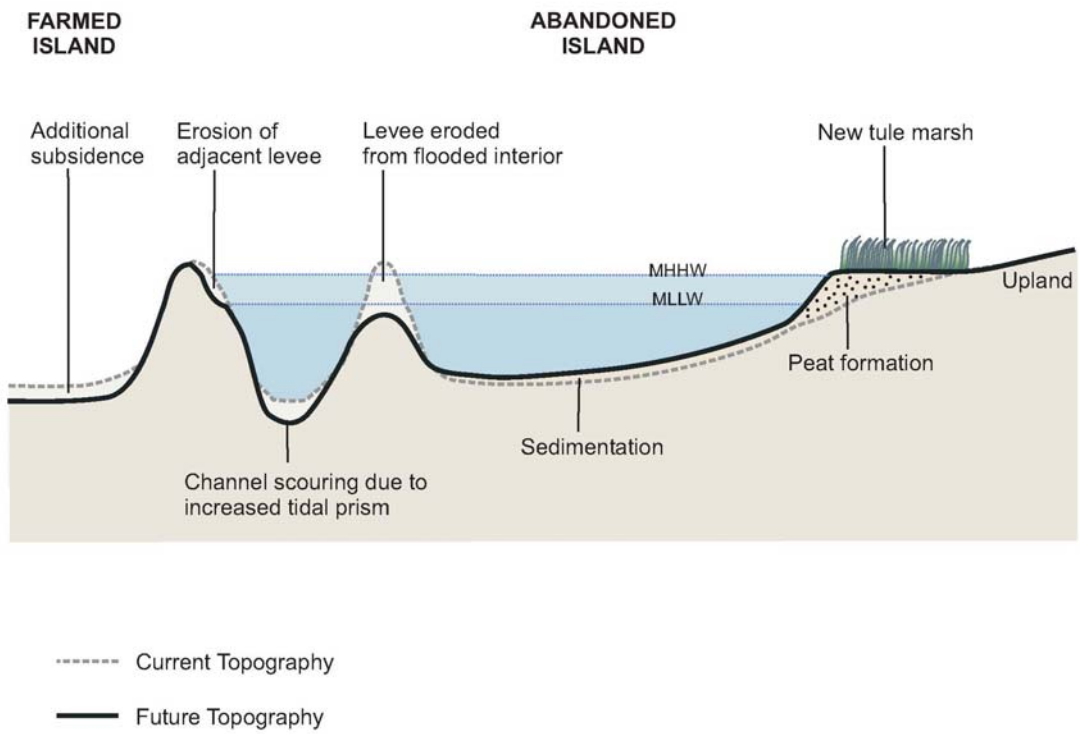

figure 7

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The Evolution of Breached Abandoned Islands in the Delta

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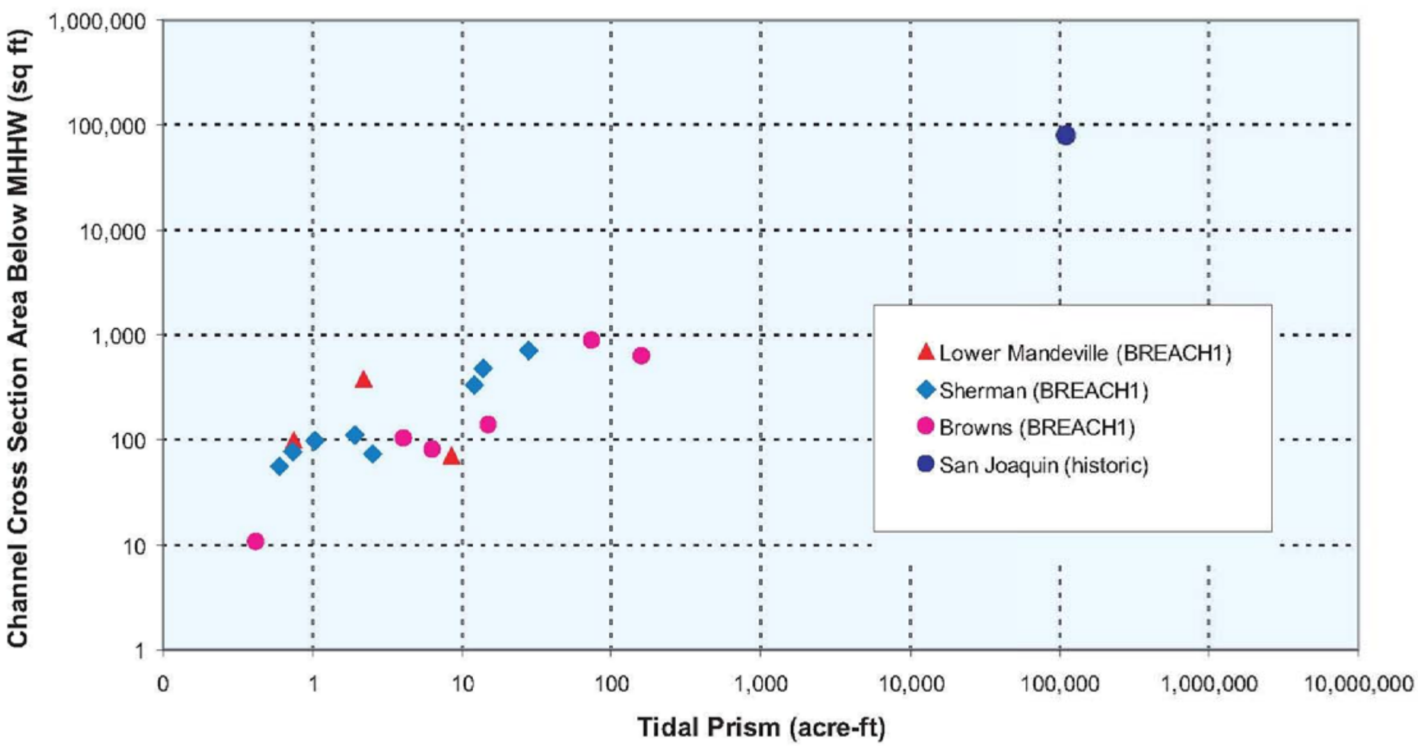

figure 8

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Hydraulic Geometry of the Delta

Source: PWA field survey

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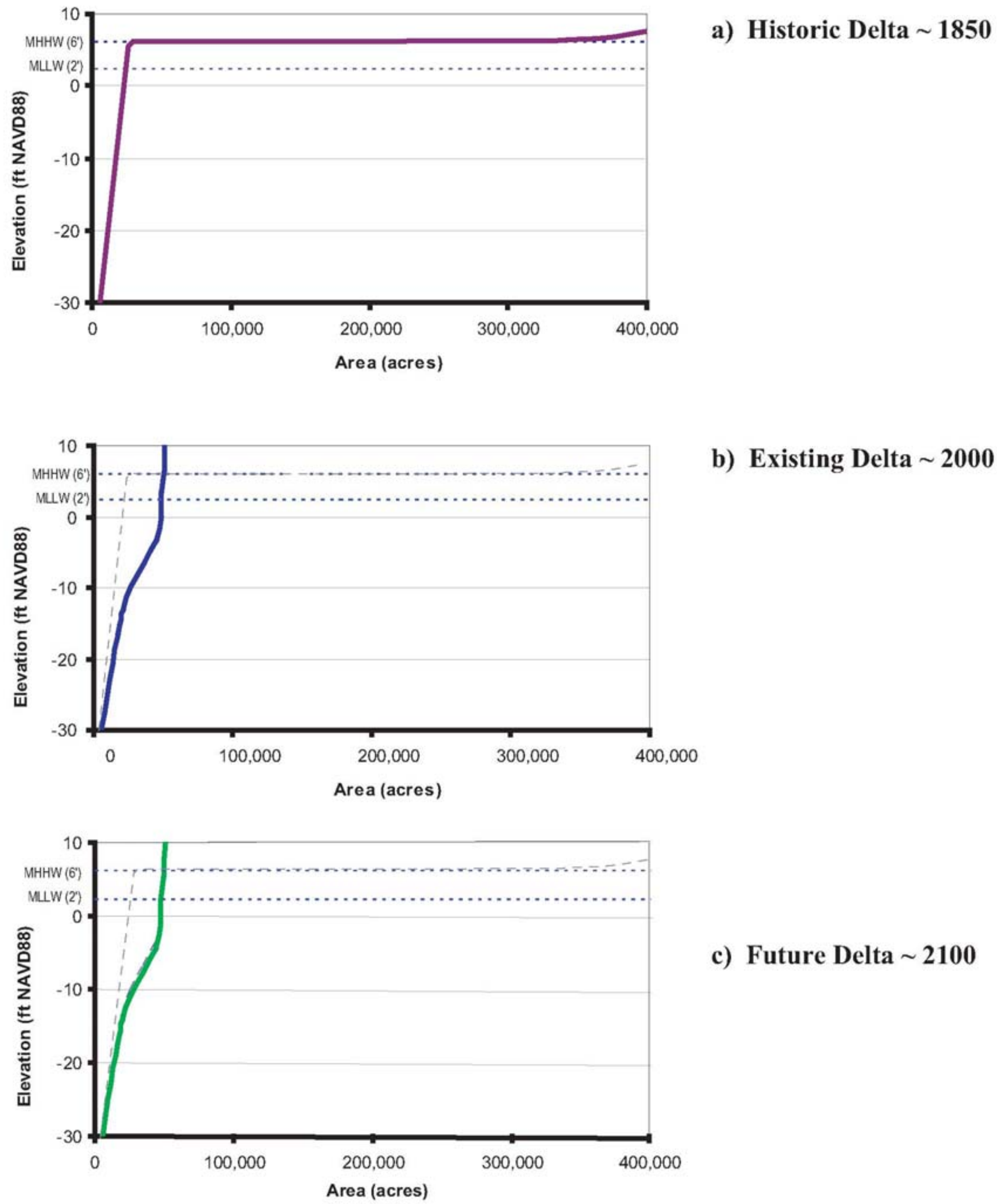

figure 9

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Change in Hypsometry under "Business as Usual" Scenario

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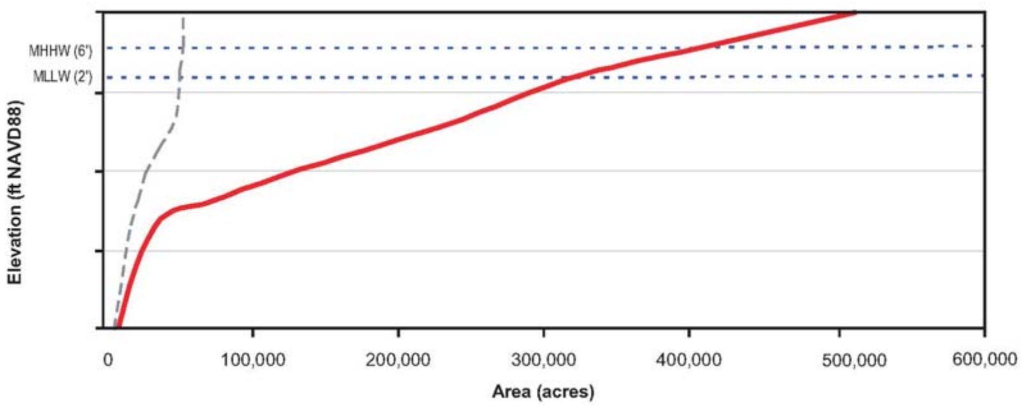
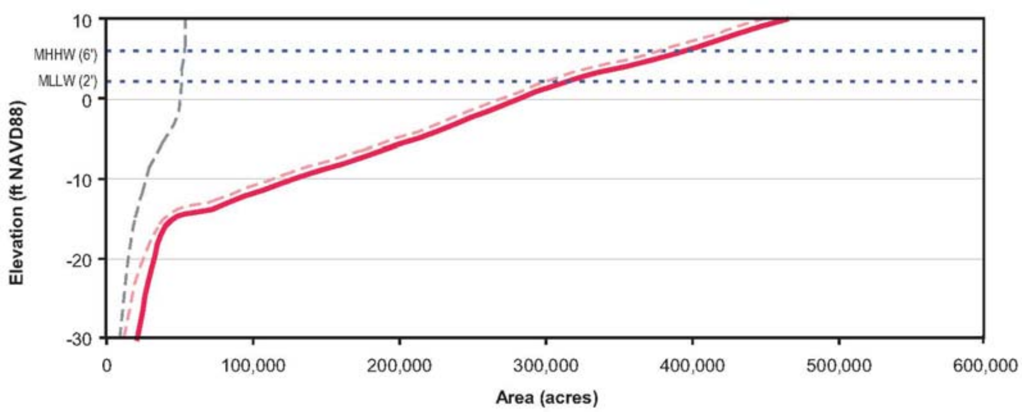
Complete Levee Failure at T + 0



Complete Levee Failure at T + 0 after 100 years



- - - - hypsometry at T + 100 with levees intact

figure 10

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Change in Hypsometry with Complete Levee Failure Scenario at T + 0

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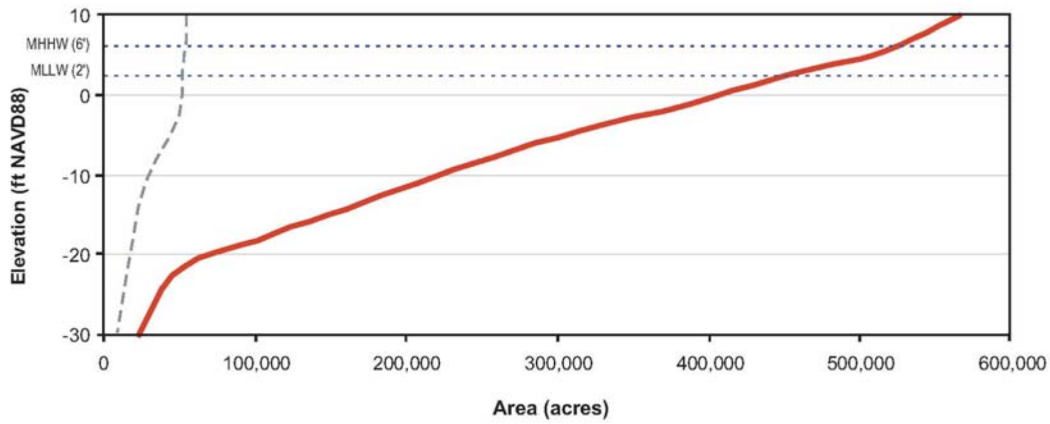

hypsometry at T + 100 with levees intact

figure 11

DRMS Geomorphic Review

Change in Hypsometry with Complete Levee Failure Scenario at T + 100

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